CWDM vertical-cavity surface-emitting laser array spanning 140 nm of the C, S, and L fiber transmission bands

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Abstract: We demonstrate record wavelength span from an 8-channel WDM VCSEL array operating CW to 65°C from 1470 to 1610 nm with precise 20-nm channel spacing. Devices are fabricated using nonplanar wafer bonding and fully-oxidized DBRs.

OCIS codes: (060.2380) Fiber optics sources and detectors; (250.7260) Vertical cavity surface emitting lasers

1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) are of great interest due to their advantages in low-cost manufacturing and packaging. These qualities are compatible with the emerging market for wideband coarse wavelength division multiplexing (CWDM) in low-cost, high-performance, optical networks spanning the entire low-loss and low-dispersion fiber transmission window from 1470 to 1610 nm. Integrating the CWDM sources in a wafer-scale fabrication process can achieve great cost savings for this application. Much work has been done on attaining wide wavelength span WDM VCSEL arrays operating near 1100 nm [1]. Wide wavelength span VCSEL arrays near 1550 nm have been more elusive however due to the challenges of fabricating high quality VCSELs in this wavelength window.

In wide wavelength span VCSEL arrays it is important to maintain uniform device performance across the elements of the array. Adjusting the cavity mode laterally across the surface of the wafer is sufficient to achieve small wavelength changes across a VCSEL array [2], however to keep the device properties uniform, controlling the alignment between the gain peak and the cavity mode is necessary in wide wavelength span CWDM VCSEL arrays. One way to maintain this alignment is to integrate multiple active regions across the surfaced of the wafer so different wavelength channels in the WDM array can utilize different active regions for gain.

In a previous report, we demonstrated a new technique, nonplanar wafer bonding, that is capable of simultaneously integrating multiple active regions across a wafer surface in a single wafer bonding step [3]. We reported the use of this technique to fabricate long-wavelength arrays with a narrow wavelength span using traditional AlGaAs distributed Bragg reflectors (DBRs) [4].

In this paper we demonstrate record wavelength span from an eight-channel long-wavelength WDM VCSEL array covering 140 nm from 1470 to1610 nm and operating CW above 65 °C. Precise 20-nm wavelength spacing and single transverse mode operation is maintained for all channels. These devices are pumped using a fiber-coupled 980-nm pump laser, a technique compatible with commercialized long-wavelength VCSELs [5]. This result is made possible by the simultaneous application of a new, simplified nonplanar wafer bonding procedure and through the use of broadband fully oxidized GaAs/AlOx DBRs [6].

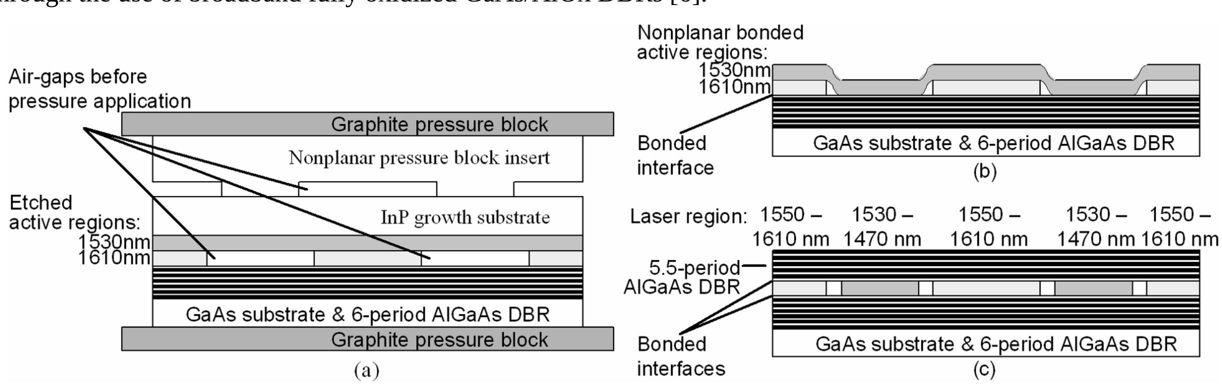

Fig. 1. Process-flow cross-section schematic of a wafer section showing: (a) nonplanar pressure block against back of step-etched InP active region wafer in bonding fixture, (b) VCSEL active regions bonded to AlGaAs DBR with InP growth substrate removed, (c) complete VCSEL array structure after bonding second AlGaAs DBR and removing GaAs substrate.

2. Array fabrication

The array fabrication process begins with two strained periodic-gain multi-quantum-well long-wavelength VCSEL active regions grown in a vertical stack on an InP wafer. The active regions have an optical-cavity length of 2.5 wavelengths at 1530 and 1610 nm and have photoluminescence peaks at 1480 and 1560 nm, respectively. In addition, the active regions have a three-period superlattice on one side for fine wavelength control in the second axis of the final two-dimensional array [4].

Nonplanar wafer bonding is used to bond the active regions to the bottom DBR of the VCSEL structure in a procedure that closely follows the technique detailed in Reference [3] and outlined here for clarity. First, the active-region wafer surface is etched with a step-shaped profile to reveal a different active region on each step level. The wafer surface is then placed in contact with an AlGaAs DBR mirror grown on a GaAs wafer. The active-region epitaxial layers are wafer bonded to the AlGaAs layers by applying pressure and heat in a graphite fixture. A reusable nonplanar pressure block insert is used adjacent to the InP substrate in the bonding fixture. Fig. 1(a) depicts the nonplanar pressure block against the backside of the InP active region wafer before pressure is applied. The nonplanar pressure block is fabricated from InP and designed to have step heights exactly equal to those on the front of the active-region wafer thus causing the wafer to conform to the AlGaAs DBR wafer surface. In this way, both active regions exposed on the surface of the InP wafer are transferred to the planar surface of the AlGaAs DBR wafer. After bonding the wafers together, the original InP growth substrate is removed, leaving the active regions attached to the AlGaAs DBR as depicted in Fig. 1(b). The excess active-region material is removed, revealing a different active region at each lateral position along the first dimension of the AlGaAs mirror. At this point, the original 3-period superlattice that was grown on each active region is etched with a step-shaped profile to trim the cavity resonance of each of the two separate active regions in the second dimension of the wafer surface. This superlattice etch forms the location of channels 1-4 on the 1530-nm active region and channels 5-8 on the 1610-nm active region. A second AlGaAs DBR is bonded by traditional planar semiconductor-direct bonding to create the final wafer structure shown in cross-section view in Fig. 1(c).

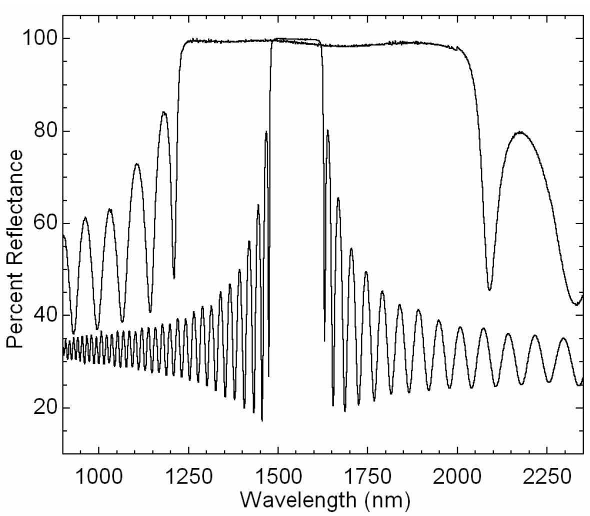

Fig. 2. Reflectivity spectrum of a 7-period fully-oxidized back mirror superimposed with reflectivity spectra from a traditional 40-period GaAs/AlAs DBR.

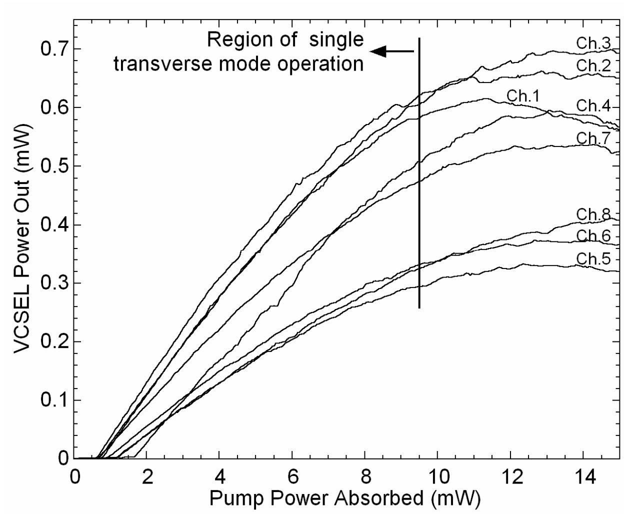

Fig. 3. VCSEL power out vs. pump power absorbed for all eight wavelength channels of a single WDM array measured at 20 °C.

In order to generate the wide reflectivity bandwidth required for a 140-nm wide WDM VCSEL array we use 5.5-period and 6-period fully-oxidized GaAs/AlOx top and bottom DBRs respectively in this VCSEL structure. The mirrors are designed to have peak reflectivity at 1540 nm after the conversion of the AlAs to AlOx by wet thermal oxidation [6]. Oxidation occurs laterally from etched trenches in a steam environment at 430 °C for 16 minutes. Fig. 2 shows the broad area reflectivity of a 7-period oxidation calibration mirror after oxidation. The rippled appearance of the stop-band is believed to be an artifact of the broad area reflectivity measurement. The reflectivity spectrum of a traditional 40-period GaAs/AlAs DBR is superimposed for comparison. A final 1540-nm anti-reflection coating is used on the surface of the device to increase the light coupled out of the VCSEL array.

3. Device Results

The final structure is an eight-channel, two-dimensional, WDM VCSEL array. The die-to-die center spacing is 1 by 1.25 mm. Channels groups 1-4 and 5-8 are spatially separated by 500 µm with an inter-channel spacing of 250 µm. All channels operate CW above 65 °C. The array is optically pumped with a 980-nm pump laser and each device has a 980-nm pump absorption efficiency of about 90 %. Fig. 3 shows the superimposed VCSEL power out vs. pump power absorbed for all eight wavelength channels measured at 20 °C from a single WDM VCSEL array. The device array has uniform thresholds of 1.185 +/- 0.5 mW and differential efficiencies that vary between 13.8 and 7.4 %. All channels operate with a side-mode suppression ratio (SMSR) in excess of 35 dB until an absorbed pump power of 9.5 mW. Fig. 4 shows the superimposed VCSEL emission spectra at a constant absorbed pump power of 14 mW for a second device array designed specifically for single-mode operation. These devices maintain a 45-dB SMSR at all pump powers and have less than 2-dB output power variation at this constant pump power.

Variation in device properties can be attributed to several factors. Wavelength channels 1-4 and 5-8 each use an active region with a peak gain near 1480 and 1560 nm respectively. Thus there is some natural variation in threshold and the rollover point due to the differing gain peak and cavity mode offset. However, there is more variation than can be attributed to this offset alone and work remains to be done to refine this integration technique.

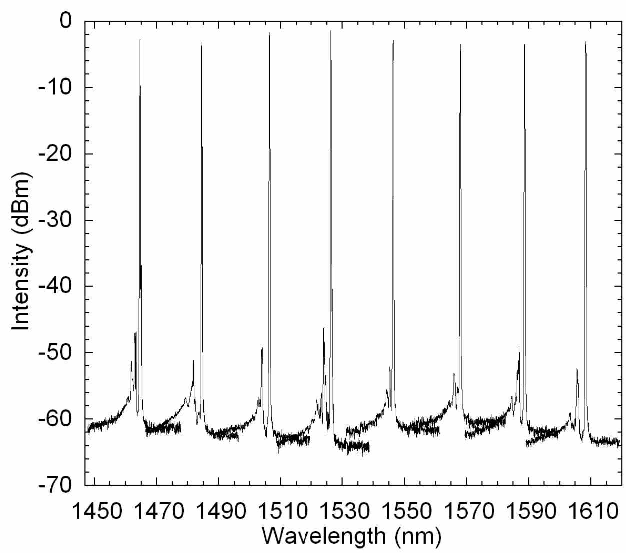

Fig. 4. Superimposed VCSEL emission spectra from the WDM VCSEL array measured at a constant absorbed pump power of 14 mW at 20 °C.

4. Conclusions

We have demonstrated record wavelength span from a long-wavelength WDM VCSEL array covering 140 nm from 1470 to 1610 nm. The devises operate beyond 65 °C and exhibit SMSR in excess of 45 dB. These devices represent a significant advance in the development of single chip sources for future use in CWDM optical network applications.

5. References

1 M. Arai, T. Kondo, A. Matsutani, T. Miyamoto, F. Koyama, “Growth of highly strained GaInAs-GaAs quantum wells on patterned substrate and its application for multiple-wavelength vertical-cavity surface-emitting laser array,” IEEE J. Select. Topics Quantum Electron., 8, 811-16 (2002).

2 A. Karim, P. Abraham, D. Lofgreen, Y. J. Chiu, J. Piprek, and J. E. Bowers, “Wafer-bonded 1.55µm vertical cavity laser arrays for wavelength division multiplexing,” Electron. Lett., 37, 431-432 (2001).

3 J. Geske, V. Jayaraman, Y. L. Okuno, and J. E. Bowers, “Vertical and lateral heterogeneous integration,” Appl. Phys. Lett., 79, 1760-1762 (2001).

4 J. Geske, Y. L. Okuno, D. Leonard, and J. E. Bowers, “Long-wavelength two-dimensional WDM vertical cavity surface-emitting laser arrays fabricated by nonplanar wafer bonding,” IEEE Photon. Technol. Lett., 15, 179-181 (2003).

5 V. Jayaraman, T. Goodnough, T. Beam, F. Ahedo, and R. Maurice, “Continuous-wave operation of single-transverse-mode 1310-nm VCSELs up to 115 degrees C,” IEEE Photon. Technol. Lett., 12, 1595-7 (2000).

6 M. H. MacDougal, P. D. Dapkus, A. E. Bond, C. Lin, and J. Geske, “Design and Fabrication of VCSEL’s with AlxOy-GaAs DBR’s,” IEEE J. Select. Topics Quantum Electron., 3, 905-915 (1997).